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Low Temperature Cu-to-Cu Bonding in Non-vacuum Atmosphere with Thin Gold Capping on Highly (111) Oriented Nanotwinned Copper

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Cu-to-Cu bonding has drawn a lot of attention as it not only has excellent electrical and thermal properties but also excellent electromigration resistance. It is believed to be a next-generation technology of IC packaging and it will help keep Moore's law effective. According to previous studies, copper direct bonding using nanotwinned copper can reduce the bonding temperature to 150°C but still requires a vacuum atmosphere. This study employed an E-gun to plate a gold layer on nanotwinned copper thin films in order to prevent oxidation. With the aid of the thin gold layer, we can prevent the oxidation of Cu surfaces and reduce the surface roughness. In this way, we achieved bonding at 200°C in N_2 and 250°C in ambient pressure with a low bonding pressure of 0.78 MPa.

Key words: Direct bonding, capping, anti-oxidation

INTRODUCTION

Moore's law predicts that the capacity for electrical components in a chip unit will double every 24 months;[1] however, it has encountered a bottleneck. With the continuous decrease of line width and pitch size, the Moore's law rate of increase may not be sustained indefinitely. With decreases of chip size and higher required performance of devices, 3D integrated circuit (3D IC) technology is regarded as the upcoming alternative technology, because 3D integration enables reduction in system size, interconnection delay, power consumption, and high integration of circuits. Solder joints were mainly used in 3D ICs for vertical interconnects between chips. However, with the decreasing size, solder joints will face issues of side wetting and formation of full intermetallic compounds (IMCs). Thus, the electromigration and formation of IMCs pose severe reliability issues for solder joints. Metal direct bonding is a promising approach for solving the issues caused by solder joints in micro-electronic packaging. Cu-to-Cu bonding draws a lot of attention, as it not only has excellent electrical and thermal properties but also has an excellent electromigration resistance.[2–4]

Cu-to-Cu direct bonding can be achieved at temperatures of 300°C to 400°C, but those temperatures are too high for processing procedures of some of microelectronic devices. In order to lower the bonding temperature, highly (111)-orientated nanotwinned copper films have been employed.

Previous studies show that the diffusivity of (111) copper is several orders greater than that of other planes in copper.[5] This is very helpful in bonding because of its high diffusivity compared to other planes, as atoms move much quicker in the (111) plane. This can effectively reduce the bonding temperature and time. Besides the diffusivity of a copper surface, the surface roughness is also a critical parameter. By controlling the two variables, we can achieve a better Cu–Cu bonding result.

Although there are many advantages in Cu–Cu bonding, the issue of copper oxide must be dealt

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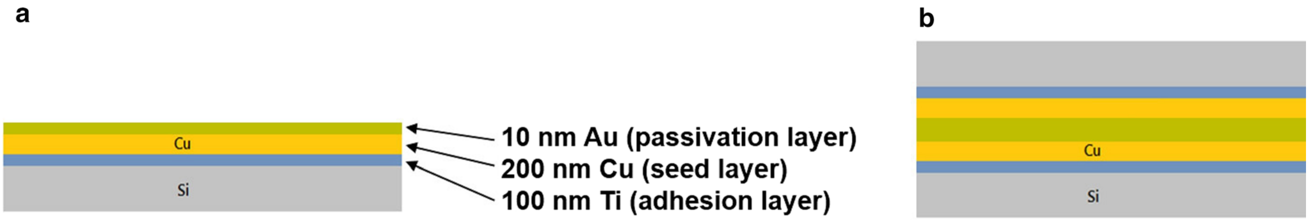

Fig. 1. (a) Schematic diagram of the sample after electroplated with nanotwinned copper and a 10 nm thin gold capping layer. (b) Schematic diagram of the sample after bonding process.

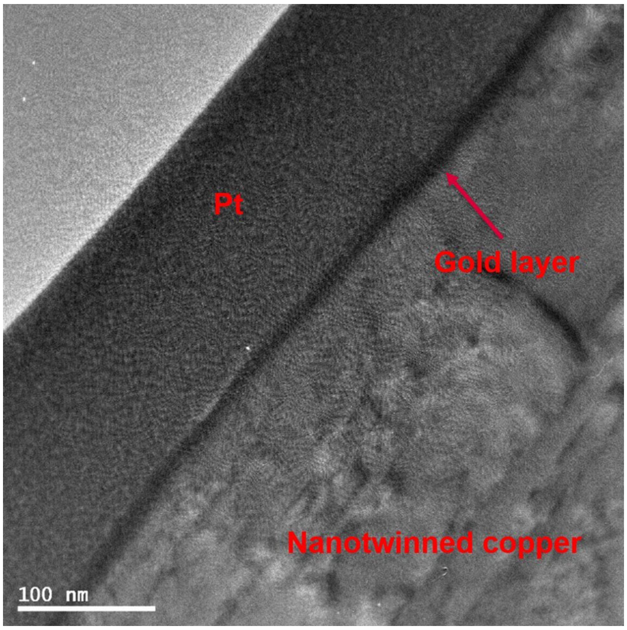

Fig. 2. TEM image of the nanotwinned film after the capping of thin layer of gold. The Pt layer is deposited before observation in order to protect the sample.

with. According to previous studies, the oxidation rate of (111)-oriented nanotwinned copper is lower than that of regular copper,[6] but still not low enough for direct bonding. Most experiments of direct bonding needed to be conducted in a vacuum environment, which makes Cu-to-Cu direct bonding hard to apply to real products. In studies, many metals or alloys have been used as a passivation layer, which can efficiently reduce surface roughness and protect the surface from oxidation.[7,8] However, a vacuum environment is still required to complete the bonding process. In this study, with a capping gold layer on highly (111)-oriented copper films, we achieved bonding at 200°C in N_2 or 250°C in air.

Another advantage of capping is reducing the surface roughness. No matter which material is used as the capping layer, capping can effectively reduce the surface roughness.[7,8] According to previous studies, lower surface roughness can effectively reduce bonding temperature and time. The surface roughness of Cu films without a capping

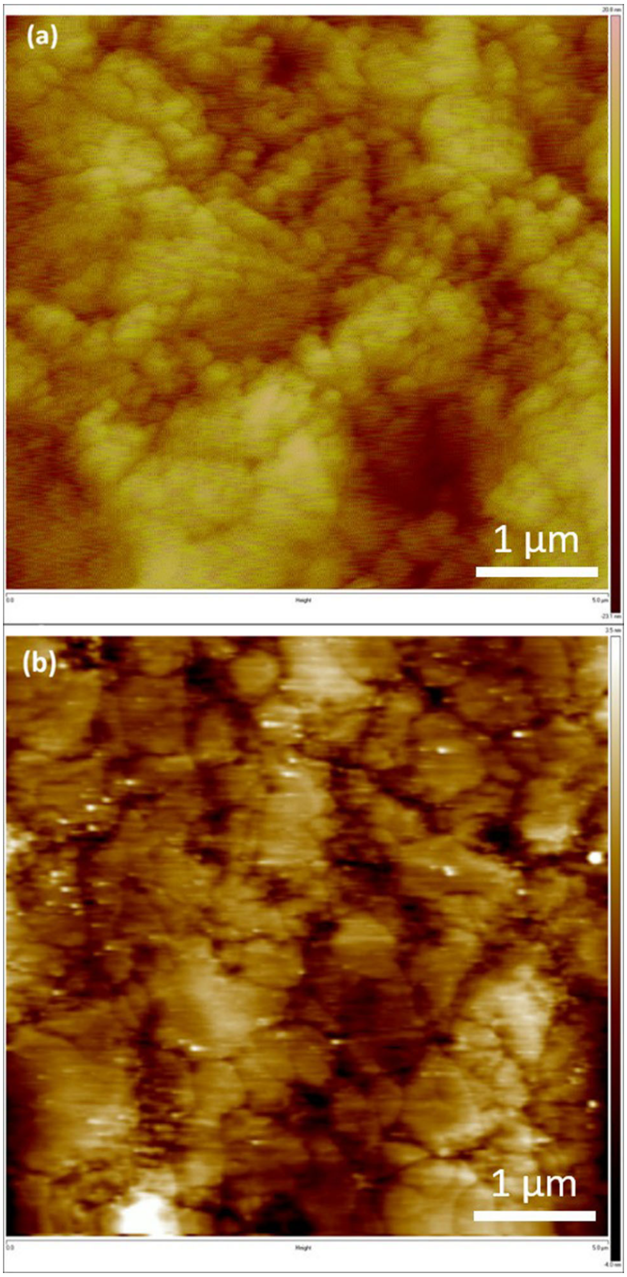

Fig. 3. (a) AFM result of Cu films before capping gold. (b) AFM result of Cu films after capping gold.

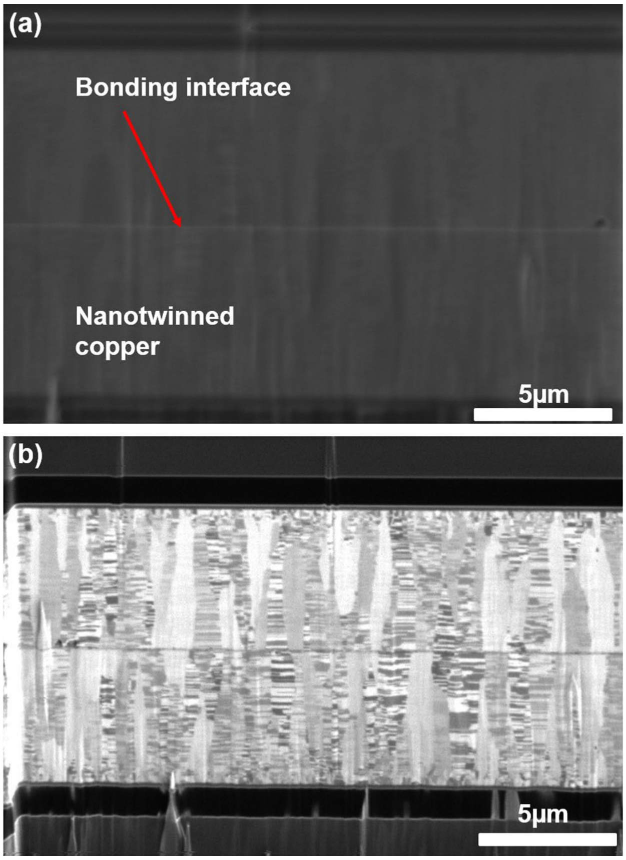

Fig. 4. (a) Electron beam image of bonding at 250°C at N2 atmosphere. (b) Ion beam image of bonding at 250°C at N2 atmosphere.

layer is 6.53 nm, and after capping a layer of gold, it decreases to 1.03 nm.

The bonding pressure is also a consideration. Chips are sensitive not only to temperature but to pressure, so decreasing the bonding pressure is also very important. In this study, we apply only approximately 0.78 MPa on the sample, which is very low compared to other studies.[9,10] This, in addition to applying a thin gold capping on nanotwinned copper, not only can reduce the bonding temperature and pressure, but also can change the required bonding atmosphere from vacuum to non-vacuum. These changes make Cu-to-Cu bonding possible and applicable in industry processes.

EXPERIMENTAL

The design of the samples is shown in Fig. 1a. On a silicon wafer, we first sputtered a 100-nm-thick Ti film as an adhesion layer and then sputtered another 200-nm-thick copper film as a seed layer. Then DC electrodeposition was applied to produce (111)-oriented nanotwinned copper films. The plating solution was composed of high concentration $CuSO_4$ solution, adding 40 ppm HCl and additive provided by Chemleader, Inc, Taiwan. The stirring rate during electroplating was 1200 rpm and current density was 8 ASD. After electroplating, we applied electropolishing to reduce surface roughness. The electropolishing solution was composed of phosphoric acid, acetic acid, and glycerin. After that, we used an E-gun to cap a 10-nm-thick gold film on the surface of the nanotwinned copper films.

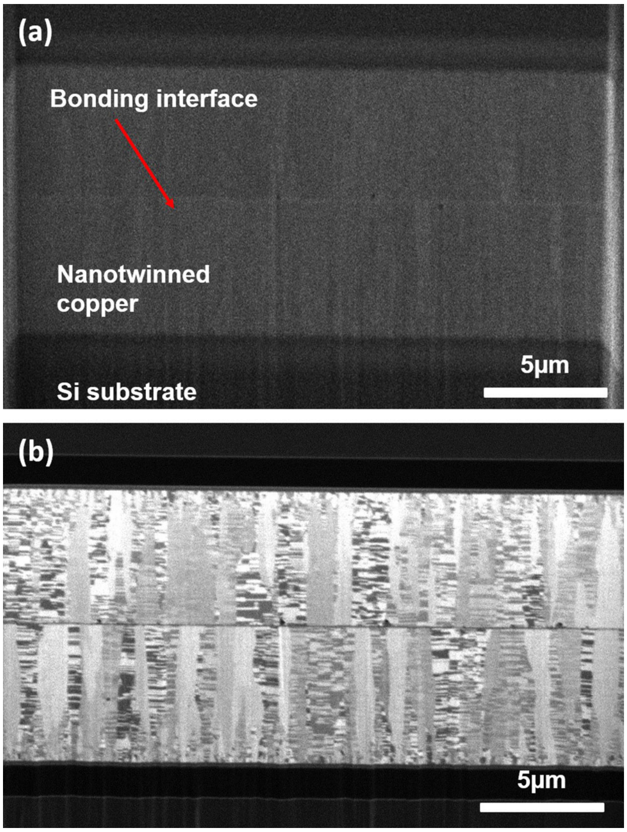

Fig. 5. (a) Electron beam image of bonding at 200°C at N2 atmosphere. (b) Ion beam image of bonding at 200°C at N2 atmosphere.

The Cu films were cut into 3×3 mm^2 pieces prior to the bonding process. Samples were cleaned by ultrasonic oscillation in acetone and then rinsed in dilute HCl solution and purged with N_2 gas. After cleaning, the pieces were placed face to face into a holder. The bonding pressure was measured to be approximately 0.78 MPa by pressure gauge at room temperature. Next we put the samples in the oven. Figure 1b shows the schematic structure for the bonding samples. The bonding conditions we used in this study were 250°C and 200°C in N_2 and 300°C and 250°C in air.

For microstructure characterization, a focused ion beam (FIB) was employed to observe the bonded interface and grain structures. Field-emission scanning electron microscope (SEM, JSM-7800F PRIME) was used to examine the voids near the bonded interfaces. The surface roughness values of the Cu films were measured using scanning probe microscopy (Veeco Dimension 3100). The microstructures of the Au capping layer were examined with a JEOL-2100 scanning transmission electron microscope (STEM).

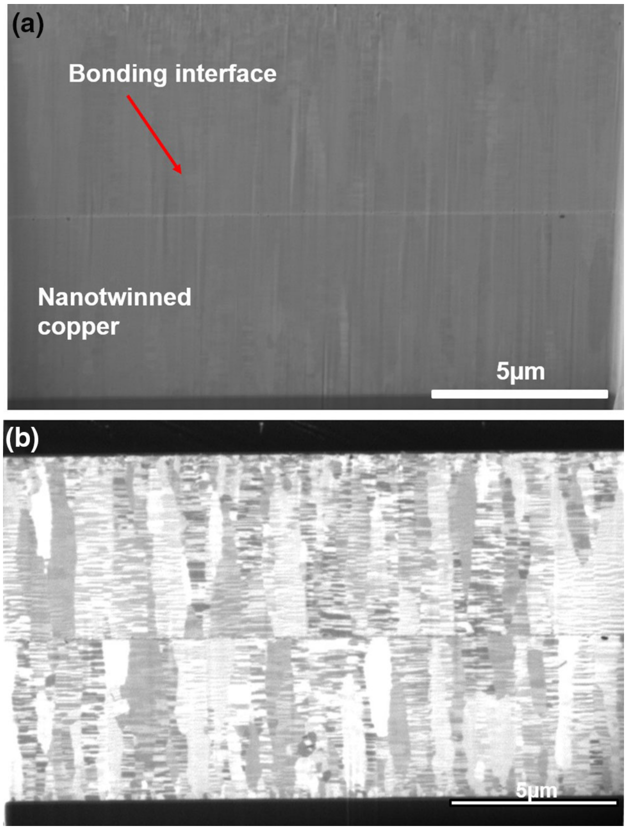

Fig. 6. (a) Electron beam image of bonding at 300°C at ambient. (b) Ion beam image of bonding at 300°C at ambient pressure.

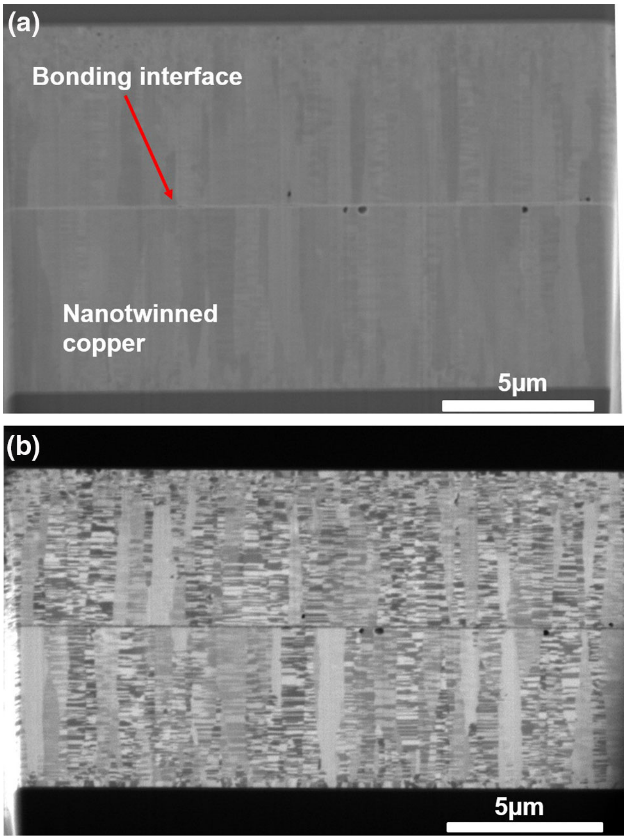

Fig. 7. (a) Electron beam image of bonding at 250°C at ambient. (b) Ion beam image of bonding at 250°C at ambient pressure.

RESULTS AND DISCUSSION

The cross-sectional TEM image of the nanotwinned films after the deposition of the capping gold is shown in Fig. 2. The thickness of gold is about 10.1 nm. In addition, the Au layer is conformal, so that it can prevent the oxidation of the Cu films. The Au capping can also reduce the surface roughness. Before the bonding process, we used atomic force microscopy (AFM) to measure to the surface roughness of the nanotwinned Cu film, and its value was 6.53 nm, as shown in Fig. 3a. However, the surface roughness reduced to only 1.03 nm after the Au capping, as presented in the AFM image in Fig. 3b. These results are consistent with previous literature. The surface roughness of a film will decrease when another thin metal layer is deposited on the film.[7,8] According to previous studies, lower surface roughness can reduce the required bonding temperature and time.[11]

With the thin Au capping, the Cu joints can be bonded successfully in an N_2 atmosphere. In this session, we have presented both electron and ion images for the bonded joints. The electron images have better spatial resolution than the ion images, while the ion images reveal the grain structures. Figure 4a shows the cross-sectional electron image of the bonded samples under the conditions of 250°C for 20 min in N_2 atmosphere. The electron image indicates that the bonding interface is nearly free of voids. Figure 4b presents the corresponding ion image of the samples in Fig. 4a. It shows that columnar grains of (111) nanotwinned Cu still remained after the annealing at 250°C for 20 min. In addition, both images indicate the Au layers still remained between the two Cu films.

Next, we lowered the bonding temperature. Figure 5 is the cross-section of bonding at 200°C for 20 min in N_2. As the picture shows, even at 200°C we still achieved good bonding quality.

After we successfully bonded in an N_2 atmosphere, we attempted direct bonding under an ambient atmosphere. Figure 6 is the result of bonding at 300°C for 20 min at ambient pressure. The bonding interface still has no voids and we did not observe oxidation, meaning the anti-oxidation properties of the thin gold layer are ideal and can help us successfully bond at ambient pressure. Figure 7 is the result of a bonding condition of 250°C for 20 min at ambient pressure. With the aid of the capped thin gold layer, we successfully bonded under an N_2 atmosphere and even bonded in ambient atmosphere pressure.

In this study, we applied a gold passivation layer on nanotwinned copper films. Due to the anti-oxidation properties of gold, we were able to complete bonding under a non-vacuum environment. Another advantage of the gold was its lower surface roughness as a capping passivation layer, which helped complete bonding at a lower temperature and time.

CONCLUSIONS

With the aid of the deposited gold layer, we can complete bonding at 200°C in N_2 and 250°C in ambient pressure with a low bonding pressure of 0.78 MPa. During the bonding process, we did not observe oxidation occurring on the samples, meaning that the gold passivation later not only can lower the surface roughness, but can also prevent oxidation occurring on the samples. These discoveries can encourage the application of methods in reducing oxidation to be used on real products.

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